Nuclear Engineering and Technology 50 (2018) 806–813

Contents lists available at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Technical Note

Analysis and radiation dose assessment of ^{222}Rn in indoor air at schools: Case study at Ulju County, Korea

ChoongWie Lee [a], Sungyeol Choi [b], Hee Reyoung Kim [a, *]

[a] Department of Nuclear Engineering, Ulsan National Institute of Science and Technology, 50, UNIST-gil, Ulsan 44919, Republic of Korea
[b] Department of Nuclear & Quantum Engineering, Korea Advanced Institute of Science and Technology, 291 Daehak-ro, Yuseong-gu, Daejeon 34141, Republic of Korea

ARTICLE INFO

Article history:
Received 26 December 2017
Received in revised form
12 March 2018
Accepted 25 March 2018
Available online 13 April 2018

Keywords:
Dose Assessments
Indoor Air
^{222}Rn
Schools
Ulju County

ABSTRACT

^{222}Rn exists in nature in the form of a rare radioactive gas. In terms of environmental radiation, issues regarding ^{222}Rn have persisted because of its radiological hazardousness. Ulju County is one of the regions of Ulsan metropolitan city, with a population of 227,699. Ulju County has the highest density of industrial complexes in Korea. In this study, ^{222}Rn radioactivity concentration was measured and analyzed in 57 schools in Ulju County using 114 passive LR-115 type detectors to secure radiological safety and confirm basic information for reduction of resident exposure to ^{222}Rn. The effective dose of ^{222}Rn was assessed to find the actual risk of the concentration surveyed in schools to human beings. The dose depended on four factors: subjects, ^{222}Rn concentration, dose coefficient, and time. The individuals subjected to dose estimation were classified into three types: students, teachers, and office workers. The subjects had different dwelling locations and times. The findings demonstrate that the radiological hazard to students and workers at schools in Ulju County owing to ^{222}Rn is negligible in terms of ^{222}Rn activity recommendation level.

© 2018 Korean Nuclear Society, Published by Elsevier Korea LLC. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

1. Introduction

The radioactive nuclide ^{222}Rn exists in nature as a colorless, odorless, and tasteless noble gas resulting from the uranium series decay chain. ^{222}Rn forms monatomic gas with 9.73 kg/m^3 density, which is approximately eight times standard atmospheric density. ^{222}Rn has a half-life of 3.8 days and decays to the stable nuclide ^{206}Pb after four alpha and four beta decays through ^{218}Po, ^{214}Pb, ^{214}Bi, and others. It can cause lung cancer (through inhalation) [1–5] and stomach cancer (through ingestion) [6,7]. The environmental radiation caused by ^{222}Rn is considered one of the most important issues in this research field because of its known dangers. Another radioisotope, ^{220}Rn, is one of the nuclides in the thorium series decay chain. Owing to the shorter half-life of this nuclide (55s), it is of less interest.

^{222}Rn is affected by many factors, such as geogenic characteristics, ventilation, building materials, and geometrical structure (e.g., cracks at wall and window positions) [8–12], and exposure rate to humans varies according to human activity [13]. Therefore, it is important to set reference buildings to survey regional differences, and schools are a suitable place to survey such differences. The geometrical structure of rooms in schools is similar across different regions, and people of different ages are regularly present. Many studies have investigated schools to find regional differences in ^{222}Rn concentrations [14–16]. Moreover, children are generally thought to be more radiosensitive than adults and likely to be at greater risk of developing certain radiation-induced types of cancer [17]. No conclusive data exist to prove that children are at greater risk from ^{222}Rn than adults [18,19], but it is difficult to say that children would not be more affected. Hence, managing the risk of ^{222}Rn concentration in schools is important. Both children and adults spend a lot of time at schools; thus, the ^{222}Rn radioactivity concentration of indoor air should be analyzed to estimate the effect of ^{222}Rn exposure.

The mean indoor air ^{222}Rn concentration in houses in Korea is 53 Bq/m^3, which is 1.35 times higher than the global average (39 Bq/m^3) [20]. In response to increased public awareness of and concerns about the hazards of ^{222}Rn, the Ministry of Environment (ME) started the “indoor ^{222}Rn control comprehensive plan” to reduce the risk caused by ^{222}Rn. The Korea Institute of Nuclear Safety started a national ^{222}Rn survey after 2000 [21–23], and

* Corresponding author.
E-mail address: kimhr@unist.ac.kr (H.R. Kim).

https://doi.org/10.1016/j.net.2018.03.020
1738-5733/© 2018 Korean Nuclear Society, Published by Elsevier Korea LLC. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

small-scale ^{222}Rn surveys and research in subway systems in Korea have been conducted at universities and institutes [24–29]. The national ^{222}Rn survey for public facilities has been conducted since 2008, based on established recommendations as a subplan of the ME indoor ^{222}Rn control comprehensive plan for ^{222}Rn reduction. Indoor air ^{222}Rn concentration has been measured in Ulju County every 2 years since 2008. The ^{222}Rn survey for government offices and elementary schools was conducted in 2008, while those for public buildings and residential houses were performed in 2009 and after 2010, respectively. However, only five of 58 schools in Ulju County were surveyed. Insufficient sampling of survey locations led to a significant analysis deviation in the estimation of ^{222}Rn effect in this area.

In the present study, an ^{222}Rn survey and analysis for 57 schools in Ulju County was performed to secure the radiological safety of students, teachers, and office workers and to provide basic information on reduction of ^{222}Rn exposure. The risk due to ^{222}Rn was calculated for different factors including subject, ^{222}Rn level, dwelling times, and dose coefficient.

2. Methods and materials

2.1. ^{222}Rn detector

A ^{222}Rn LR-115 type passive detector, one of the detectors used to measure the time integral concentration of ^{222}Rn in air, was used to survey ^{222}Rn concentration in schools in Ulju County. The detector has a hollow cylindrical form with 4 cm diameter and 3 cm height (Fig. 1) [30]. The detector consists of a filter, a detection part, and a connection part. The filter prevents inert gases other than ^{222}Rn, from reaching the detection unit, thereby minimizing the effects of radioactive substances other than ^{222}Rn. The detector has a solid-state track detector (SSTD) film, which forms chemical imperfections because of the damage of the atomic arrangement in the path of charged particles [31]. Thus, ^{222}Rn passes through the filter by diffusion and emits alpha particles that create tracks on the SSTD surface. The depth of the alpha particles on the SSTD is on the order of a few tens of micrometers. The number of tracks generated is converted to the ^{222}Rn concentration to derive it at the measurement point. The tracks created by the alpha particles are not directly readable using an optical microscope. Hence, etching was performed with 10% NaOH at 60°C for 150 min to enlarge the tracks and allow analysis by optical microscope. The average number of tracks in the unit area was converted to the ^{222}Rn concentration. The correlation between the ^{222}Rn concentration and the tracks is presented as follows [32]:

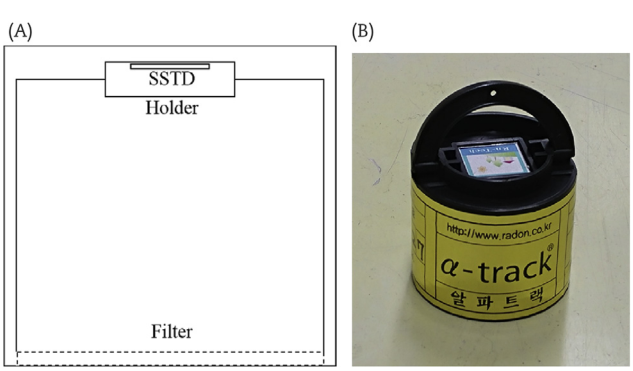

Fig. 1. (A) Schematics of LR-115 type II detector. (B) Actual shape of LR-115 type II detector.
SSTD, solid-state track detector.

Fig. 2. School location in Ulju County.

$$37y = 0.800x - 40.167 \quad (1)$$

where x is the number of tracks with unit area (Tr/cm^2), and y is the ^{222}Rn concentration (Bq m^3/day).

2.2. Survey design

A total of 57 of the 58 schools in Ulju County (one school was under reconstruction) were surveyed: 33 elementary, 13 middle, and 11 high schools. Figs. 2 and 3 show the locations of the schools and a geological map of Ulju County. The geology of Ulju County consists mostly of Mesozoic Cretaceous feature, except for alluvium, which is of Cenozoic age.

^{222}Rn concentration is lowest in summer and highest in winter [33–35]. Hence, it was planned to measure ^{222}Rn during the summer and the winter and during the middle season. ^{222}Rn was

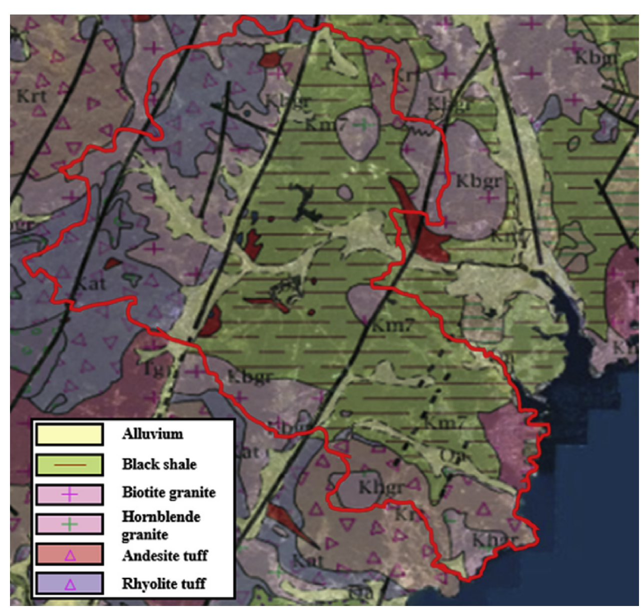

Fig. 3. Geological map in Ulju County.

thus measured during summer, autumn, and winter to observe the increase of ^{222}Rn concentration in Ulju County. June to August was defined as summer, September to November as autumn, and December to February as winter. Three months were included for each season. We visited each school and set up detectors; it took 2 weeks to install devices and collect the data. A detector was placed in each of two rooms in each school for 3 months, unless it went missing or serious damage occurred during the survey. The number of lost or seriously damaged detectors was four in the summer, four in the autumn, and three in the winter, which seemed to have resulted from the instrument being small in size, open to students, and difficult to manage in a continuous manner, making it easier for students to touch and for device to be damaged or lost. The measurement site was set up in similar rooms to suppress the occurrence of the same problem. The detectors were collected after 3 months and sent to Rn-tech, the manufacturer of the detectors, to analyze the track density in the detector and determine the indoor air ^{222}Rn concentration. The series of analysis procedures were completed within a week. The detectors were kept sealed in Rn tight containers to prevent additional ^{222}Rn exposure until they were sent. The detectors were gathered and replaced every 3 months in all locations. The measured ^{222}Rn concentration of the detectors can be affected by thoron. Hence, they were placed at a distance of 1 m or more from the walls, floors, and ceilings. The detectors were hung from a string or turned upside down to allow air to circulate and prevent the inlet from closing.

The indoor air ^{222}Rn concentrations between the seasons were compared. Moreover, the average and standard deviation were calculated for the elementary, middle, and high schools. The measured data were compared with the level recommended by the ME (148 Bq/m^3), which is the same as the level recommended by the US Environmental Protection Agency (4 pCi/L), to find whether an additional ^{222}Rn reduction program was needed. The survey results were then compared with those of the national ^{222}Rn survey, including that conducted in Ulju County, performed by the ME in 2008. Raduet was used for the ^{222}Rn survey in 2008. This detector can detect ^{222}Rn and ^{220}Rn at the same time. Hence, the influence of ^{220}Rn can be relatively excluded by the short range of ^{220}Rn caused by its short half-life. The detectors were installed in ground floor offices to avoid loss and damage. The measurement dates start from June 2008, and it was agreed the month that this study began [23,36].

2.3. Regulation

^{222}Rn concentration is regulated by the Indoor Air Quality Control in Public Use Facilities Act ME. The reference level of ^{222}Rn concentration is 148 Bq/m^3, which is the same as the level recommended by the Environmental Protection Agency. Annual limit of intake for ^{222}Rn is 3 MBq, and derived air concentration is 1,000 Bq/m^3 at allowable exhaust standards.

The International Commission on Radiological Protection (ICRP) provides guidelines for ^{222}Rn regulation in indoor air at home and in the work place. ICRP recommends that exposure be maintained below 10 mSv per year [37]. Based on this level, ICRP recommends limiting ^{222}Rn concentration to 300 Bq/m^3 at home and to 1,000 Bq/m^3 in the work place, considering dwelling time spent in each area.

3. Dose calculations for ^{222}Rn

A dose assessment was implemented to decide on the actual health risk caused by ^{222}Rn. The effective dose depends on three factors: subjects, ^{222}Rn concentrations, and dose coefficient.

3.1. Subjects

Three kinds of people (students, office workers, and teachers) were assumed to dwell in schools, and each individual provided their behavior scenario at the school. Students are the dominant type of people in schools, and they spend most of their time in classrooms. Meanwhile, office workers stay in the office and teachers stay in two places in schools (offices and classrooms) during class hours. In terms of age, two types of people spend time in schools. The first is adults, including teachers and office workers. The second is children, the students. The dose calculations involved scenarios including what types of subjects dwelled in specific locations and where the doses were estimated considering the different human respiratory tract models between children and adults. The effective dose was assessed for these subjects following each scenario.

Thus, there are three kinds of schools and three kinds of people in schools, so nine scenarios were derived for ^{222}Rn dose assessment of schools in Ulju County.

3.2. ^{222}Rn concentrations

The ^{222}Rn concentrations were the results of surveyed indoor air ^{222}Rn concentrations. Surveyed ^{222}Rn concentration was classified according to the scenario of each subject. The ^{222}Rn concentrations of each place for those subjects who dwell in two places in schools (i.e., classrooms and offices) were calculated accordingly.

3.3. Dose coefficient

Many researchers have tried to determine the dose coefficient of adults through epidemiological or simulation studies [38–43]. The International Commission on Radiological Protection collected research data on the dose coefficient of ^{222}Rn. They recommended that the effective dose per unit exposure at home should be 12 mSv per work level month, which is a single coefficient for use in most circumstances [37,44–46]. This coefficient can be converted to 4.5×10^{-6} mSv/(Bq h/m^3) with an equilibrium factor of 0.4, which is the generally assumed value for the equilibrium state [47–50].

It is reported from human respiratory tract model analysis that this dose delivered to lungs is relatively insensitive to subject age [51]. Children have a lower breathing rate than adults, and their intakes are lower. However, the target tissue mass of children is also smaller, which causes the same effect in terms of effective dose. Therefore, the same dose coefficient of ^{222}Rn in adults is used in children.

3.4. Calculations

The effective dose during measurement time D_e is calculated as follows using the ^{222}Rn concentration, dose coefficient, and time [37]:

$$D_e = \sum A_s \times C_{eff} \times t_{dwell,s} \tag{2}$$

where A_s is the ^{222}Rn concentration at the location at the season S (Bq/m^3); C_{eff} is the dose coefficient [1.76×10^{-2} mSv/(Bq/m^3)] at an equilibrium factor of 0.4; and $t_{dwell,S}$ is the dwelling time at the season S (hours).

4. Results and discussion

4.1. Survey results

Table 1 and Figs. 4–7 show the seasonal variation of ^{222}Rn concentration in elementary, middle, and high schools in Ulju County. The solid line is a trend line drawn using the collected data.

Table 1
Results of the ^{222}Rn survey for 57 schools during three seasons.

Seasons	^{222}Rn concentration of indoor air (Bq/m^3)			
	Elementary schools	Middle schools	High schools	Overall
Summer (Jun–Aug)	47	38	43	44
Autumn (Sep–Nov)	54	36	38	47
Winter (Dec–Feb)	66	39	40	55
A.M.	56	38	40	49
S. D.	44	14	18	36
G.M.	42	33	35	37
G.S.D	1.8	1.5	1.4	1.7

A.M., arithmetic mean; G.M., geometric mean; G.S.D., geometric standard deviation; S.D., standard deviation.

The averages of the indoor air ^{222}Rn concentration for the three seasons were less than the level recommended by the ME (148 Bq/m^3). All four graphs show log normal distribution. As a result of fitting the graph, the R-square values are shown to be 0.95, 0.87, and 0.91 for the season and 0.96 for the annual average. The ^{222}Rn concentration values of the elementary schools were higher than those of the middle and high schools. The elementary school buildings in Ulju County are older than the middle and high school buildings by almost 20 years. Therefore, ^{222}Rn concentration, some of which was contributed from geogenic Rn infiltrating through cracks, was thought to be relatively higher. Derived using the MATLAB code, Fig. 8 presents the geographical ^{222}Rn distribution of Ulju County in summer, autumn, and winter and the average values.

The ^{222}Rn at two locations was below the recommended level in summer but increased as the season changed to winter. The overall average eventually exceeded the recommended level.

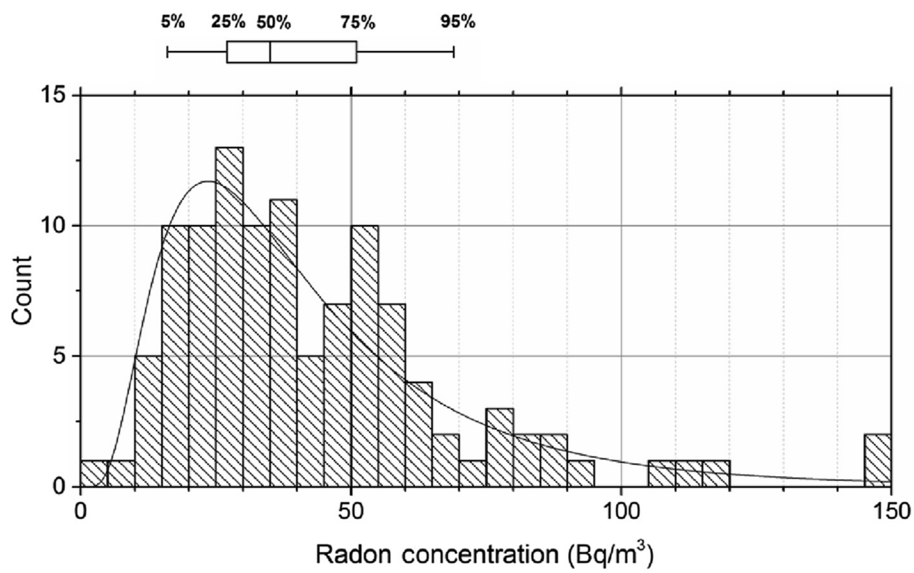

Fig. 4. ^{222}Rn concentration distribution at schools in summer.

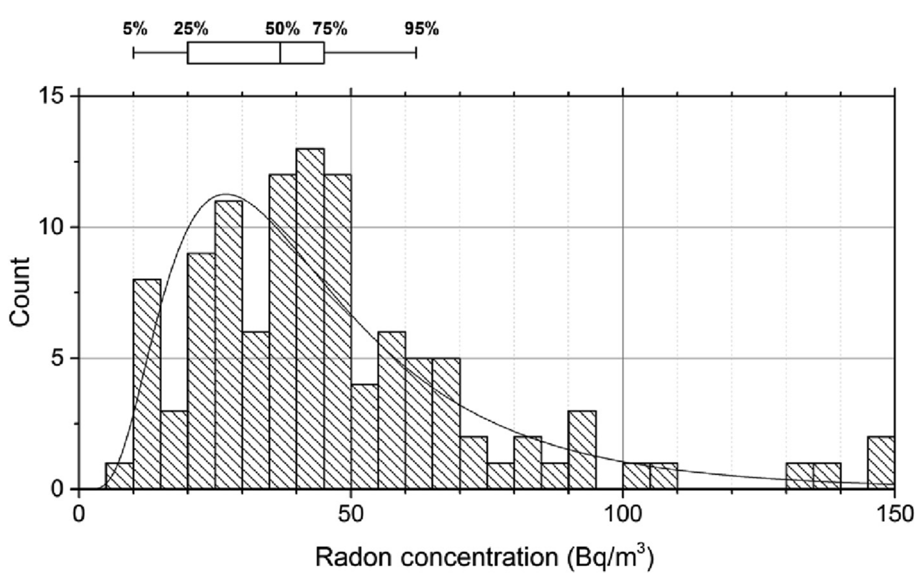

Fig. 5. ^{222}Rn concentration distribution at schools in autumn.

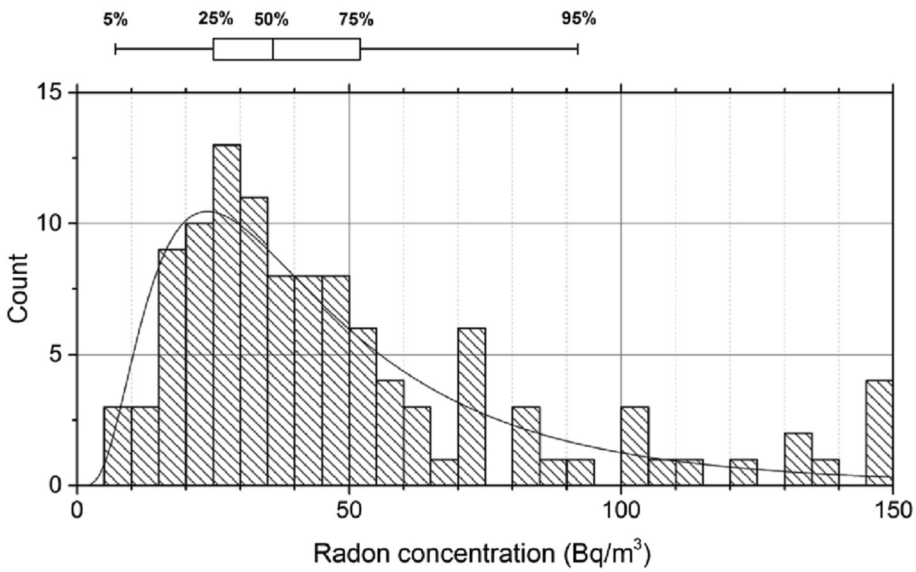

Fig. 6. ^{222}Rn concentration distribution at schools in winter.

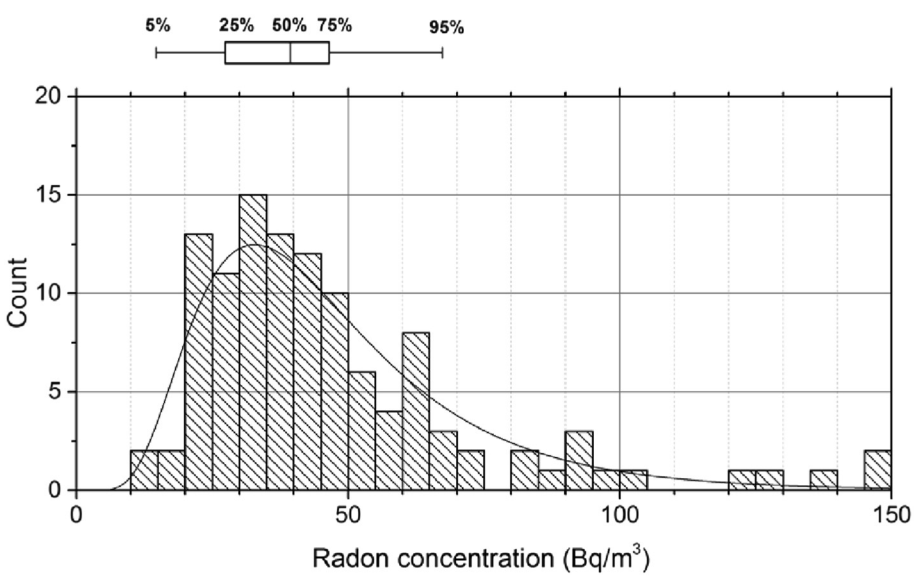

Fig. 7. Average ^{222}Rn concentration distribution at schools.

The survey data were compared with those obtained by the ME in 2008 (Table 2). The 2008 survey was limited to an elementary school office; thus, only relevant data were compared. The average indoor air ^{222}Rn concentration for the three seasons, except spring, was surveyed and found to be 156 Bq/m^3 and 51 Bq/m^3 in 2008 and 2015, respectively; ^{222}Rn concentration in this survey showed lower values. The data from 2008 were thought to have low representativeness of Ulju County and high deviation from true values because of the small number of sampling points ($n = 5$). The present measurements for 33 elementary schools indicated the possibility of large variation caused by the characteristics of different sampling locations, including the geogenic variation of the ^{222}Rn concentrations. The average of the five highest values herein was 94 Bq/m^3, which was lower than previously obtained figures. Accordingly, a one-way analysis of variance (ANOVA) test was performed for the two data distributions. The p value was then derived to find any statistical difference between the variances of the two distributions. A p value less than 0.05 denoted a difference between the two distributions, while that of 0.0006 indicated a difference between the two results.

The statistical results of the survey for the seasons were analyzed through a one-way ANOVA. Table 3 presents the corresponding results. The survey results demonstrated a difference in the average of the ^{222}Rn concentration. From a statistical point of view, the p value for the seasons in elementary schools was at least 0.12, which was a small value compared to 0.88 and 0.78 for the middle and high schools, respectively. This value was not enough to prove a difference in the ^{222}Rn concentration in the air of the schools during different seasons.

Classifying the location of each school according to a geological map, ^{222}Rn concentration as a geological feature is shown in Table 4.

Schools in Ulju County have at least one of six geological features: alluvium, black shale, biotite granite, hornblende granite,

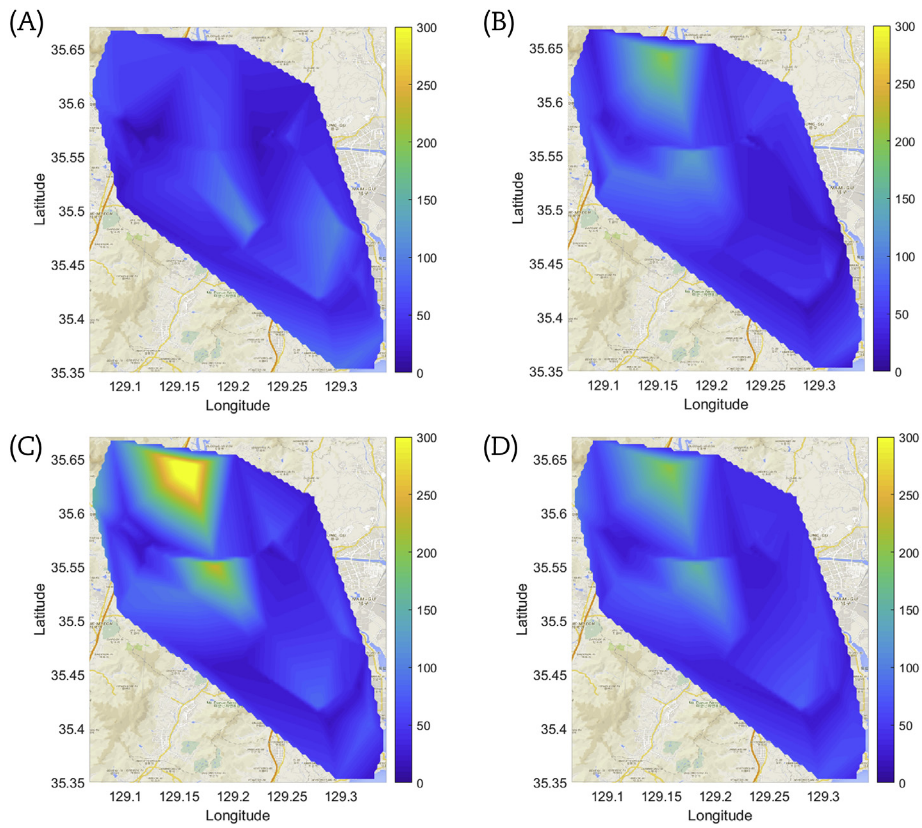

Fig. 8. ^{222}Rn mapping in Ulju County. (A) At summer. (B) At autumn. (C) At winter. (D) At average.

andesite tuff, and rhyolite tuff. The number of schools on alluvium is highest at 32, followed by black shale at 16. Among the geological features, ^{222}Rn concentration on biotite granite was the highest (97.12 Bq/m^3).

Table 2
Comparison of ^{222}Rn survey with previous survey.

Survey date	Number of schools	Indoor ^{222}Rn concentration (Bq/m^3)				
		Summer	Autumn	Winter	Spring	Average (except spring)
2008	5	68.0	226.9	173.3	97.7	156
2015	16	37	51	57	–	51

Table 3
One-way ANOVA results for seasonal variation.

School type	Square mean	F ratio	*p* value	F rejection value
Elementary schools	6586	2.14	0.12	3.04
Middle schools	50	0.13	0.88	3.13
High schools	192	0.25	0.78	3.15
Overall	3658	1.75	0.18	3.02

ANOVA, analysis of variance.

Table 4
^{222}Rn concentration as a geological feature (Bq/m^3).

Geological features	Number	Average	S. D.
Alluvium	32	45	26
Black shale	16	44	18
Biotite granite	4	97	83
Hornblende granite	3	47	21
Andesite tuff	1	57	–
Rhyolite tuff	1	64	–

S.D., standard deviation.

4.2. *Dose assessment for ^{222}Rn*

4.2.1. *^{222}Rn concentrations*

The effective dose was assessed by seasonal concentration. First, the measurement places in schools were classified into two, as follows: classroom (i.e., classroom, science room, and library, which the students mainly use) and office (i.e., administration office and teachers' room, which the office workers and teachers mainly use). Figs. 9 and 10 illustrate the activity concentrations depending on the type of place (e.g., classroom and office).

The ^{222}Rn concentration in the elementary school classrooms was the highest at 55 Bq/m^3. Both the middle-school classrooms and offices had the lowest ^{222}Rn concentration at 36 Bq/m^3.

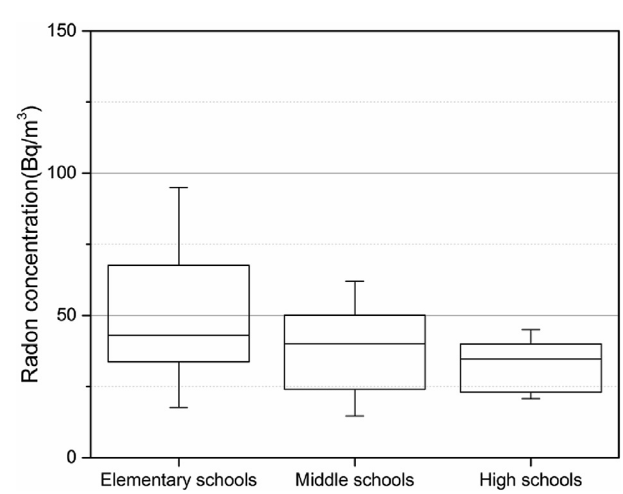

Fig. 9. ^{222}Rn concentration in classrooms at schools.

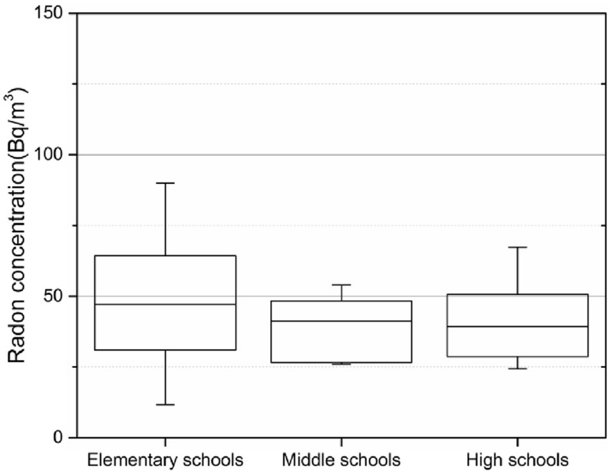

Fig. 10. ^{222}Rn concentration in offices at schools.

Standard deviations were calculated in the order of 47, 15, 8 Bq/m^3 in classrooms and 30, 12, and 20 Bq/m^3 in the offices of each elementary school, middle school, and high school. In terms of the type of place, the concentration in the classrooms was 15% higher than that in the offices. The statistical analysis results using a *t* test imply that the difference between classroom and office cannot be verified because the *p* value was 0.25, higher than 0.05.

4.2.2. Dwelling time

The subjects who stay in the school had different regulation times. In dose calculation, we applied annual statutory class hours for students and the working hours of 2000 h for teachers and officers, which was the normal Organization for Economic Co-operation and Development (OECD) working hours [52]. The class and working hours for students and teachers, respectively, were equally divided by week, excluding the weeks that included vacations and Thanksgiving Day. The residence time for each season was derived as shown in Table 5 considering the time of the survey and the period of vacation. A difference between the working and class hours was found in the case of teachers.

The dwelling times of students and teachers in spring and autumn were higher because of the long summer and winter vacation in schools. Moreover, the residence time increased in class as the student moved from elementary to high school.

4.2.3. Dose calculations

Table 6 shows the effective dose during the measured periods for students, teachers, and office workers calculated for each type of school.

In Table 6, the children have the lowest effective dose because of their smallest dwelling time. The highest effective dose from ^{222}Rn in elementary school was 0.41 mSv. The office workers had the highest effective dose among all subjects because they had the highest dwelling time.

Table 5
Reference time at schools.

Subjects	School type	Spring (Mar~May)	Summer (Jun~Aug)	Autumn (Sep~Nov)	Winter (Dec~Feb)
Student	Elementary school	287	199	265	155
	Middle school	326	226	301	176
	High school	367	254	338	197
Teachers	All	482	334	445	260
Office workers	All	500	500	500	500

Table 6
Annual effective dose from ^{222}Rn (mSv).

Subjects	Elementary schools	Middle schools	High schools
Children	0.27 ± 0.05	0.19 ± 0.02	0.20 ± 0.01
Teachers	0.42 ± 0.07	0.28 ± 0.03	0.28 ± 0.02
Office worker	0.54 ± 0.07	0.42 ± 0.04	0.49 ± 0.07
Average	0.41 ± 0.04	0.29 ± 0.02	0.32 ± 0.03

4.2.4. Error analysis

Surveyed ^{222}Rn concentration is an average value over 3 months. The students and the teachers do not stay in the classroom or office, except during class hours or working hours. There is a difference in ventilation frequency according to whether people are present or not; ^{222}Rn concentration is lower when people are present. In this experiment, average ^{222}Rn concentration is used, which leads to an overestimation of the dose to people in schools. The phenomenon that nighttime had higher values than daytime has also been investigated in other articles [53,54].

In the present survey, the detector was installed on the ground floor, which was expected to have higher ^{222}Rn concentrations than the upstairs floors [55,56]. General schools had many ground floor rooms, including administrative rooms and rooms for special classes. Therefore, ^{222}Rn may be overestimated because the space in which ordinary students spend time was in the upper floors. In schools, additional time is spent in school besides class time, for example supplementary study time and break time, which is not considered in this study. Actual residence time may be higher and, therefore, the dose received may be higher.

5. Conclusions

The indoor air ^{222}Rn radioactivity concentration of 57 schools in Ulju County, including elementary, middle, and high schools, was analyzed using an integrated LR-115 dosimeter. Most schools in Ulju County maintain a level below the maximum recommended level of ^{222}Rn radioactivity. However, some showed a concentration above the recommended level of 148 Bq/m^3. Some areas with high ^{222}Rn concentrations are assumed to be due to the presence of biotite granite.

The dose assessment was conducted based on the types of schools and the main dwellers at the schools. The results show that elementary school office workers had the highest dose at 0.54 mSv. The ICRP recommendation limit is 10 mSv per year, so the ^{222}Rn concentration is over the level recommended by the ME; however, it was found to be an acceptable level when the surveyed results were converted into dose. The present survey results and dose assessment provide baseline data for establishing a ^{222}Rn reduction policy at schools in Ulju County. A long-term survey and statistical analysis will be needed to find accurate local ^{222}Rn characteristics of indoor air, depending on variables such as building age and the geological features of a rural/urban area.

Conflicts of interest

The authors declare no conflicts of interest.

Acknowledgments

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIP: Ministry of Science, ICT and Future Planning) NRF-

2016M2B2B1945082, NRF-22A20153413555. This work was also supported by the Ulju County Office and the Ulsan Metropolitan Office of Education.

References

[1] A. Gray, S. Read, P. McGale, S. Darby, Lung cancer deaths from indoor radon and the cost effectiveness and potential of policies to reduce them, BMJ 338 (2009) a3110.
[2] R.E. Thompson, D.F. Nelson, J.H. Popkin, Z. Popkin, Case-control study of lung cancer risk from residential radon exposure in Worcester County, Massachusetts, Health Phys. 94 (2008) 228–241.
[3] T.K. Sethi, M.N. El-Ghamry, G.H. Kloecker, Radon and lung cancer, Clin. Adv. Hematol. Oncol. 10 (2012) 157–164.
[4] M.C. Turner, D. Krewski, C.A. Pope III, Y. Chen, S.M. Gapstur, M.J. Thun, Long-term ambient fine particulate matter air pollution and lung cancer in a large cohort of never-smokers, Am. J. Respir. Crit. Care Med. 184 (2011) 1374–1381.
[5] D. Tchorz-Trzeciakiewicz, M. Kłos, Factors affecting atmospheric radon concentration, human health, Sci. Total Environ. 584 (2017) 911–920.
[6] A. Auvinen, L. Salonen, J. Pekkanen, E. Pukkala, T. Ilus, P. Kurttio, Radon and other natural radionuclides in drinking water and risk of stomach cancer: a case-cohort study in Finland, Int. J. Canc. 114 (2005) 109–113.
[7] M. Kreuzer, B. Grosche, M. Schnelzer, A. Tschense, F. Dufey, L. Walsh, Radon and risk of death from cancer and cardiovascular diseases in the German uranium miners cohort study: follow-up 1946–2003, Radiat. Environ. Biophys. 49 (2010) 177–185.
[8] C. Sainz, L.S. Quindós, I. Fuente, J. Nicolás, L. Quindós, Analysis of the main factors affecting the evaluation of the radon dose in workplaces: the case of tourist caves, J. Hazard Mater. 145 (2007) 368–371.
[9] B.P. Jelle, Development of a model for radon concentration in indoor air, Sci. Total Environ. 416 (2012) 343–350.
[10] N. Hunter, C.R. Muirhead, J.C. Miles, J.D. Appleton, Uncertainties in radon related to house-specific factors and proximity to geological boundaries in England, Radiat. Protect. Dosim. 136 (2009) 17–22.
[11] K. Akbari, J. Mahmoudi, M. Ghanbari, Influence of indoor air conditions on radon concentration in a detached house, J. Environ. Radioact. 116 (2013) 166–173.
[12] M. Máduar, M. Campos, B. Mazzilli, F. Villaverde, Assessment of external gamma exposure and radon levels in a dwelling constructed with phosphogypsum plates, J. Hazard Mater. 190 (2011) 1063–1067.
[13] K. Yu, B. Lau, D. Nikezic, Assessment of environmental radon hazard using human respiratory tract models, J. Hazard Mater. 132 (2006) 98–110.
[14] F. Bochicchio, Z. Žunić, C. Carpentieri, S. Antignani, G. Venoso, V. Carelli, C. Cordedda, N. Veselinović, T. Tollefsen, P. Bossew, Radon in indoor air of primary schools: a systematic survey to evaluate factors affecting radon concentration levels and their variability, Indoor Air 24 (2014) 315–326.
[15] A. Clouvas, S. Xanthos, G. Takoudis, Indoor radon levels in Greek schools, J. Environ. Radioact. 102 (2011) 881–885.
[16] S. Rahman, J. Anwar, A. Jabbar, M. Rafique, Indoor radon survey in 120 schools situated in four districts of the Punjab Province-Pakistan, Indoor Built Environ. 19 (2) (2009) 214–220.
[17] G. Kendall, T. Smith, Doses from radon and its decay products to children, J. Radiol. Prot. 25 (2005) 241.
[18] ICRP, in: Protection Against radon at Home and at Work, 65, ICRP Publication, 1993.
[19] ICRP, in: 1990 Recommendations of the International Commission on Radiological Protection, ICRP Publication 60, International Commission on Radiological Protection, 1991.
[20] W.H. Organization, WHO Handbook on Indoor Radon: a Public Health Perspective, World Health Organization, 2009.
[21] C.-K. Kim, Y.-J. Kim, H.-Y. Lee, B.-U. Chang, S. Tokonami, 220 Rn and its progeny in dwellings of Korea, Radiat. Meas. 42 (2007) 1409–1414.
[22] C.-K. Kim, S.-C. Lee, D.-M. Lee, B.-U. Chang, B.-H. Rho, H.-D. Kang, Nationwide survey of radon levels in Korea, Health Phys. 84 (2003) 354–360.
[23] KINS, KINS-GR-300, in: Assessment of Radiation Risk for the Korean Population, 2005.
[24] D.-S. Kim, Y.-S. Kim, Distributions of airborne radon concentrations in Seoul metropolitan subway stations, Health Phys. 65 (1993) 12–16.
[25] S. Yoon, B.-U. Chang, Y. Kim, J.-I. Byun, J.-Y. Yun, Indoor radon distribution of subway stations in a Korean major city, J. Environ. Radioact. 101 (2010) 304–308.
[26] Jae sik Jeon, Deok chan Kim, Yeong ung Park, Ji yeong Lee, Sang su Lee, Nam jin Kim, Min yeong Kim, in: Analysis on the Distribution of High Level Radon and Reduction Strategy at Subway Platform, Korean Society for Atmospheric Environment, 2006, pp. 552–553.
[27] M.H. Song, B.-U. Chang, Y. Kim, K.-W. Cho, Radon exposure assessment for underground workers: a case of Seoul subway police officers in Korea, Radiat. Protect. Dosim. 147 (2011) 401–405.
[28] S.-B. Kwon, Y. Cho, D. Park, E.-Y. Park, Study on the indoor air quality of Seoul metropolitan subway during the rush hour, Indoor Built Environ. 17 (2008) 361–369.
[29] J.-g. Lee, S.-h. Byeon, J.-h. Lee, ICCAS-SICE, 2009, in: The Effect of Platform Screen Door (PSD) for Fine Particles at Subway Train in Seoul, Korea, IEEE, 2009, pp. 1707–1710.
[30] Y.W. Park, Alpha Track Detector with Foldable Semicircle Ring, in, Google Patents, 2007.
[31] D. Nikezic, K. Yu, Optical characteristics of tracks in solid state nuclear track detectors studied with ray tracing method, Nucl. Track Detect. Des. Meth. Appl. (2009) 177–195. Chapter 5.
[32] Y.W. Park, in: Principle and Method of Measurement of Alpha Track Detector, Korea Occupational Safety and Health Administration Seminar, 2015.
[33] S. Rahman, N. Mati, B. Ghauri, Seasonal indoor radon concentration in the North West Frontier Province and federally administered tribal areas—Pakistan, Radiat. Meas. 42 (2007) 1715–1722.
[34] T. Ramachandran, T. Muraleedharan, A. Shaikh, M.S. Ramu, Seasonal variation of indoor radon and its progeny concentration in a dwelling, Atmos. Environ. Part A Gen. Top. 24 (1990) 639–643.
[35] M. Faheem, N. Mati, Seasonal variation in indoor radon concentrations in dwellings in six districts of the Punjab province, Pakistan, J. Radiol. Prot. 27 (2007) 493.
[36] K.S. Lee, S.Y. Seo, Y.J. Kim, K.H. Choi, B.S. Son, A study on the indoor radon concentration of elementary school in Korea, Kor. Soc. Indoor Environ. 9 (2012) 127–133.
[37] ICRP, Recommendations of the International Commission on Radiological Protection, 37, Ann. ICRP, 2007.
[38] D. Annex, Sources and Effects of Ionizing Radiation, 125, Investigation of I, 1977.
[39] R. Winkler-Heil, W. Hofmann, J. Marsh, A. Birchall, Comparison of radon lung dosimetry models for the estimation of dose uncertainties, Radiat. Protect. Dosim. 127 (1–4) (2007) 27–30.
[40] J. Marsh, A. Birchall, K. Davis, Comparative dosimetry in homes and mines: estimation of K-factors, Radioact. Environ. 7 (2005) 290–298.
[41] J.W. Marsh, J.D. Harrison, D. Laurier, E. Blanchardon, F. Paquet, M. Tirmarche, Dose conversion factors for radon: recent developments, Health Phys. 99 (2010) 511–516.
[42] A. Birchall, A. James, Uncertainty analysis of the effective dose per unit exposure from radon progeny and implications for ICRP risk-weighting factors, Radiat. Protect. Dosim. 53 (1994) 133–140.
[43] J. Porstendörfer, Physical parameters and dose factors of the radon and thoron decay products, Radiat. Protect. Dosim. 94 (2001) 365–373.
[44] ICRP, ICRP Main Commission Meeting, April 13–17, in, Sydney. Australia.
[45] ICRP, The 2007 Recommendations of the International Commission on Radiological Protection, 37, ICRP Publication, 2007, pp. 2–4, 103, Ann. ICRP.
[46] ICRP, Lung Cancer Risk from Radon and Progeny and Statement on Radon, 40, ICRP Publication, 2010, 115, Ann. ICRP.
[47] H. Hötzl, R. Winkler, Long-term variation of outdoor radon equilibrium equivalent concentration, Radiat. Environ. Biophys. 33 (1994) 381–392.
[48] A. Cavallo, The radon equilibrium factor and comparative dosimetry in homes and mines, Radiat. Protect. Dosim. 92 (2000) 295–298.
[49] S. Singh, R. Malhotra, J. Kumar, L. Singh, Indoor radon measurements in dwellings of Kulu area, Himachal Pradesh, using solid state nuclear track detectors, Radiat. Meas. 34 (2001) 505–508.
[50] Y. Kim, B.-U. Chang, H.-M. Park, C.-K. Kim, S. Tokonami, National radon survey in Korea, Radiat. Protect. Dosim. 146 (2011) 6–10.
[51] J. Marsh, A. Birchall, Sensitivity analysis of the weighted equivalent lung dose per unit exposure from radon progeny, Radiat. Protect. Dosim. 87 (2000) 167–178.
[52] R.C. Valle, S. Normandeau, G.R. González, Education at a Glance Interim Report: Update of Employment and Educational Attainment Indicators, Organisation for Economic Co-operation and Development (OECD), 2015.
[53] J. Vaupotič, N. Smrekar, Z.S. Žunić, Comparison of radon doses based on different radon monitoring approaches, J. Environ. Radioact. 169 (2017) 19–26.
[54] P. Kolarž, D. Filipović, B. Marinković, Daily variations of indoor air-ion and radon concentrations, Appl. Radiat. Isot. 67 (2009) 2062–2067.
[55] C. Man, H. Yeung, Modeling and measuring the indoor radon concentrations in high-rise buildings in Hong Kong, Appl. Radiat. Isot. 50 (1999) 1131–1135.
[56] H. Al-Khateeb, A. Al-Qudah, F. Alzoubi, M. Alqadi, K. Aljarrah, Radon concentration and radon effective dose rate in dwellings of some villages in the district of Ajloun, Jordan, Appl. Radiat. Isot. 70 (2012) 1579–1582.